

Laboratory Validation of Space Coronagraph Technologies

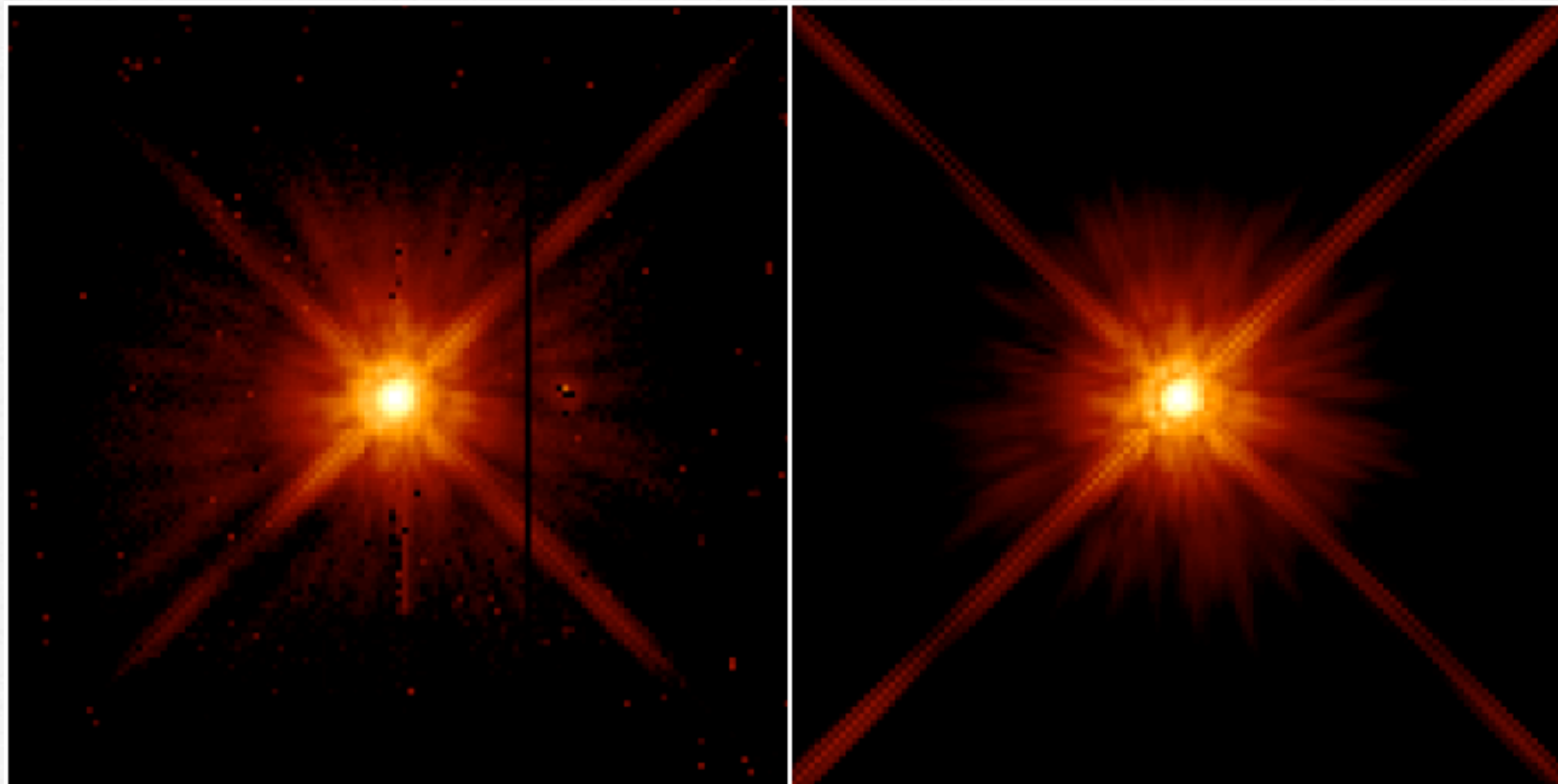
John Trauger, JPL

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Overview

- ❑ Space offers the best opportunity for direct imaging of nearby planetary systems.
- ❑ Challenge of high contrast space imaging is separable into two main areas:
 - ❑ Coronagraph a promising concept for the suppression of **diffracted** light.
 - ❑ Precision wavefront correction is required for suppression of **scattered** light.
- ❑ Concepts for coronagraph design, corrective optics, and control algorithms have been modeled and shown to work in the mathematical exactitude of the computer.
- ❑ HCIT provides our first opportunity to bring these ideas together for development in a laboratory setting.
- ❑ HCIT experiments test the models -- these models guide experiments on the HCIT.
- ❑ Early results are encouraging, and experimentation is ongoing.

HST Point Spread Function



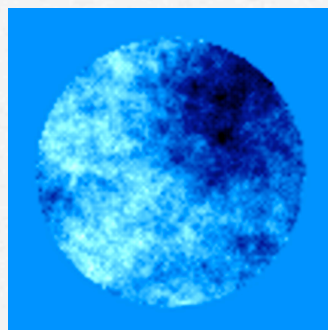
Measured (WFPC2)

Calculated

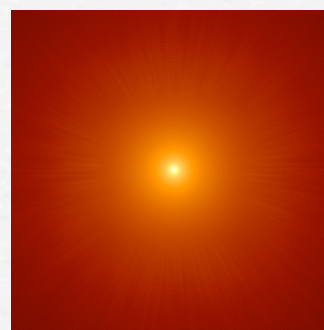
Calculated PSF -- based on HST pupil geometry and measured surface figure of the HST primary mirror -- closely resembles measured PSF

Schematic of an Actively Corrected Lyot Coronagraph

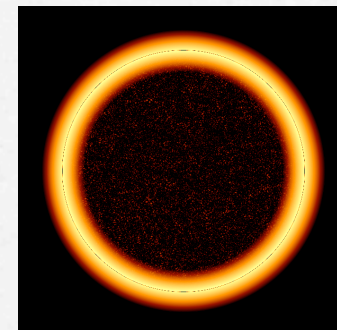
Uncorrected wavefront



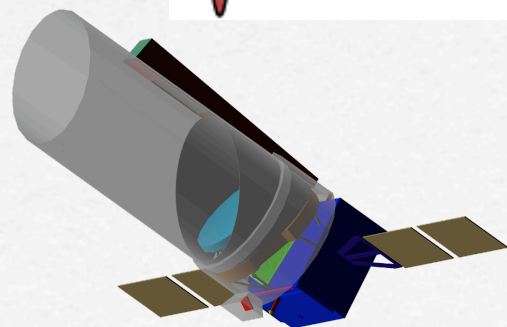
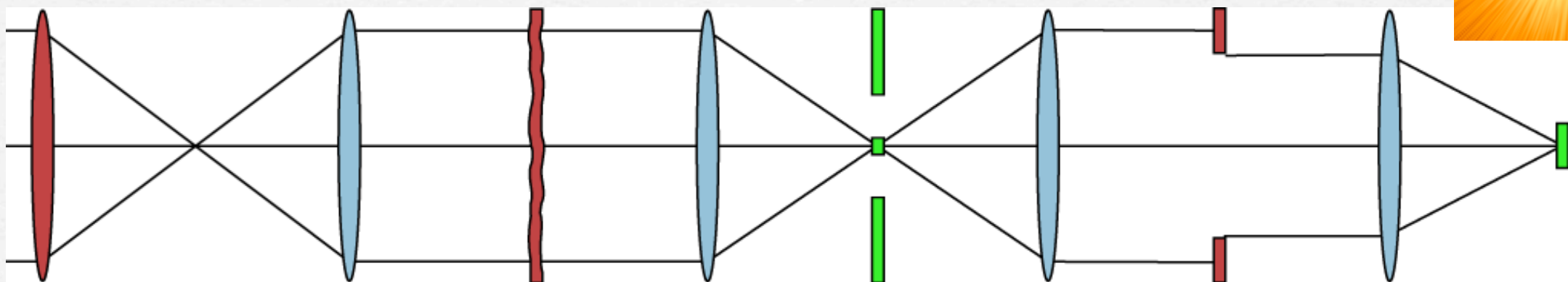
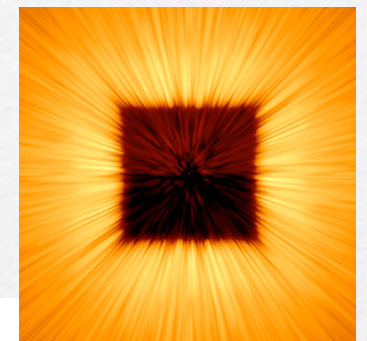
Corrected star image



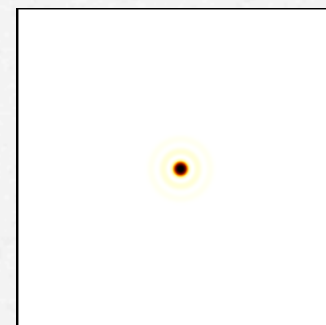
Illumination at pupil plane



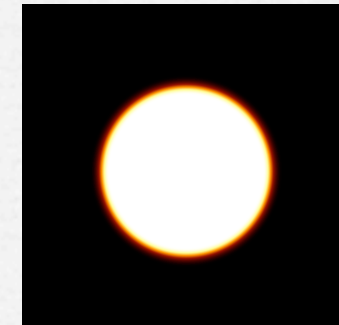
High contrast coronagraphic field



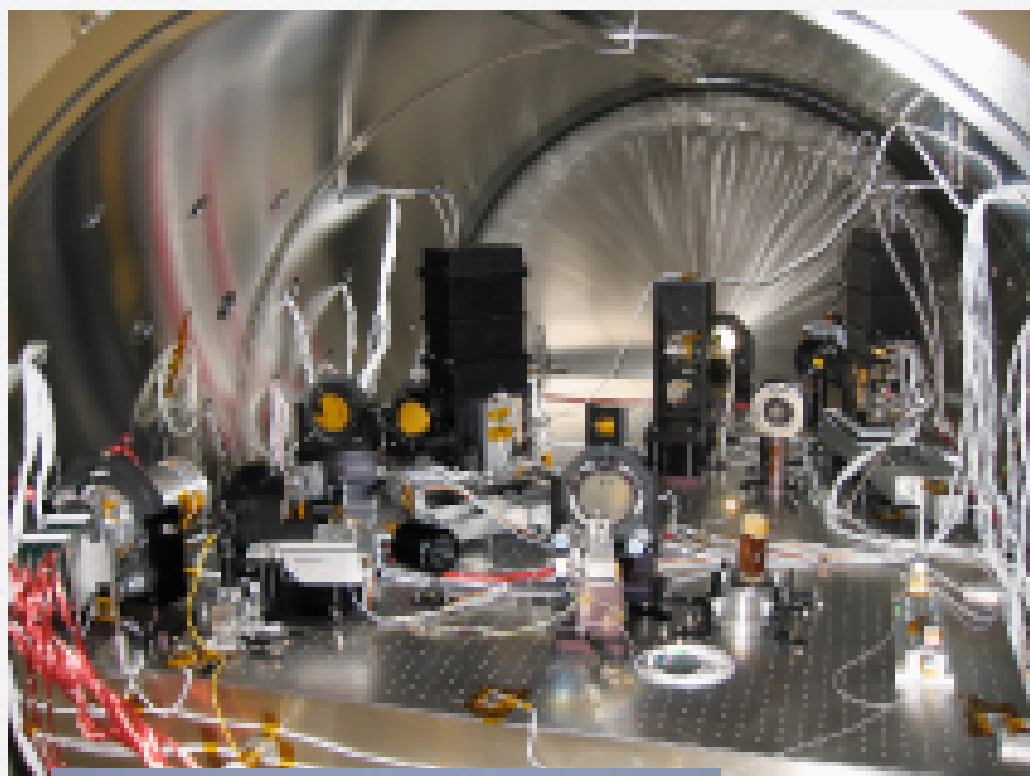
Deformable mirror



Occulting mask

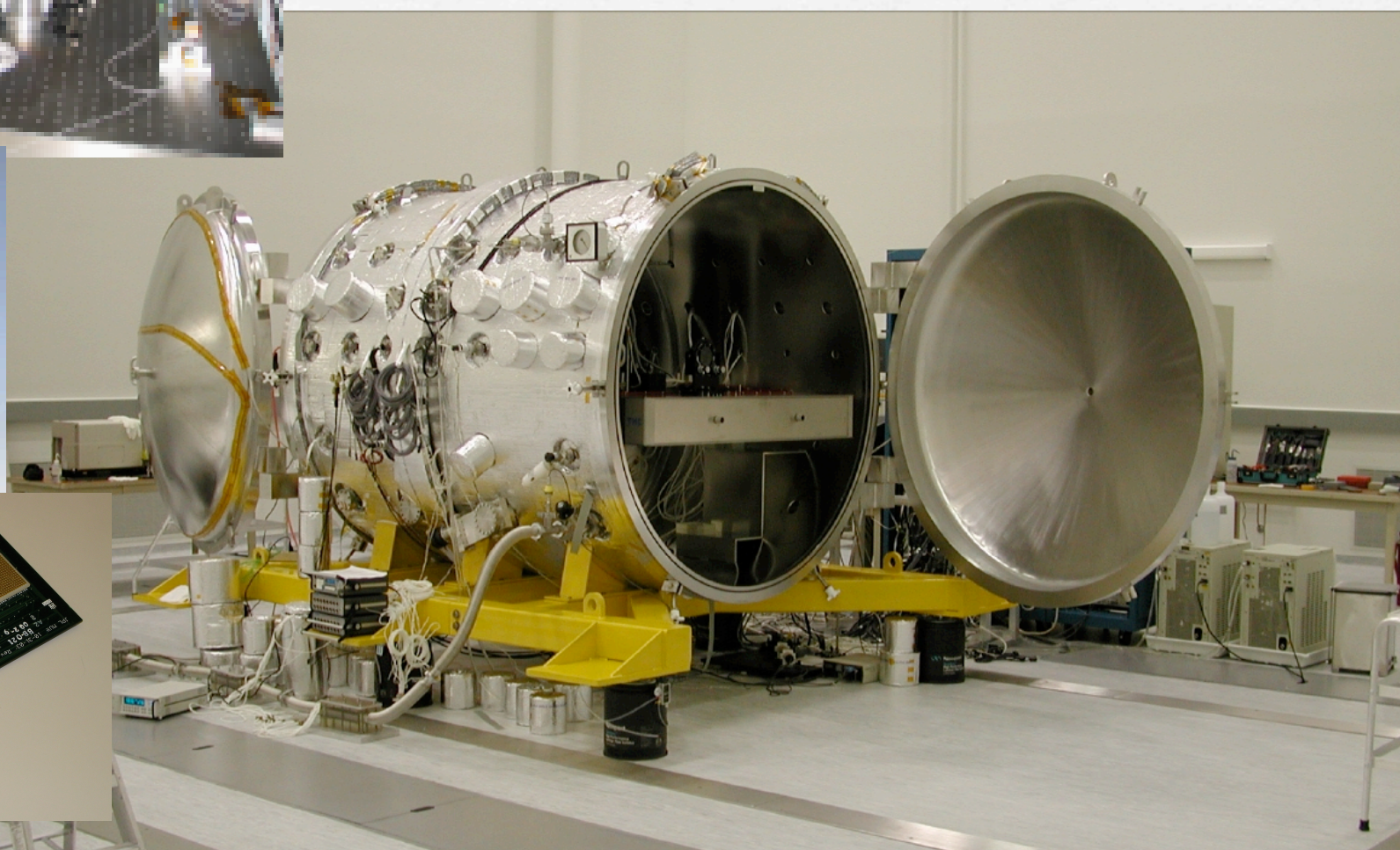
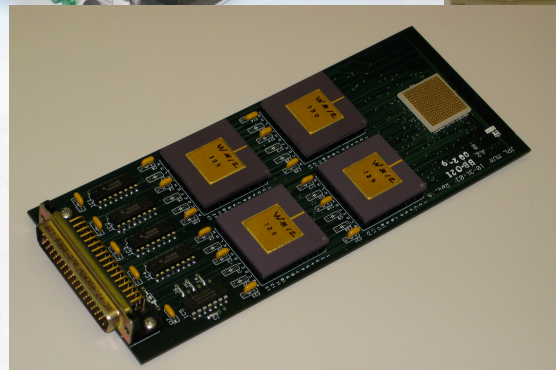
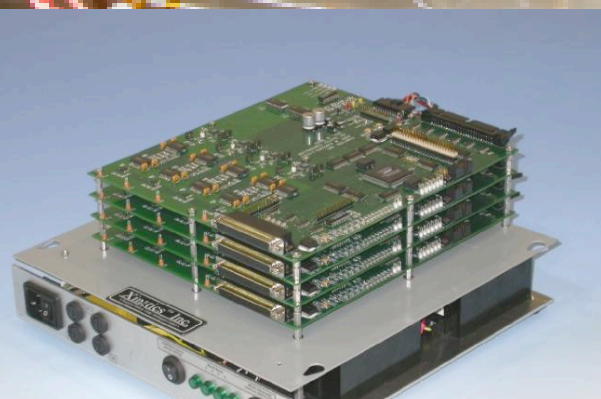


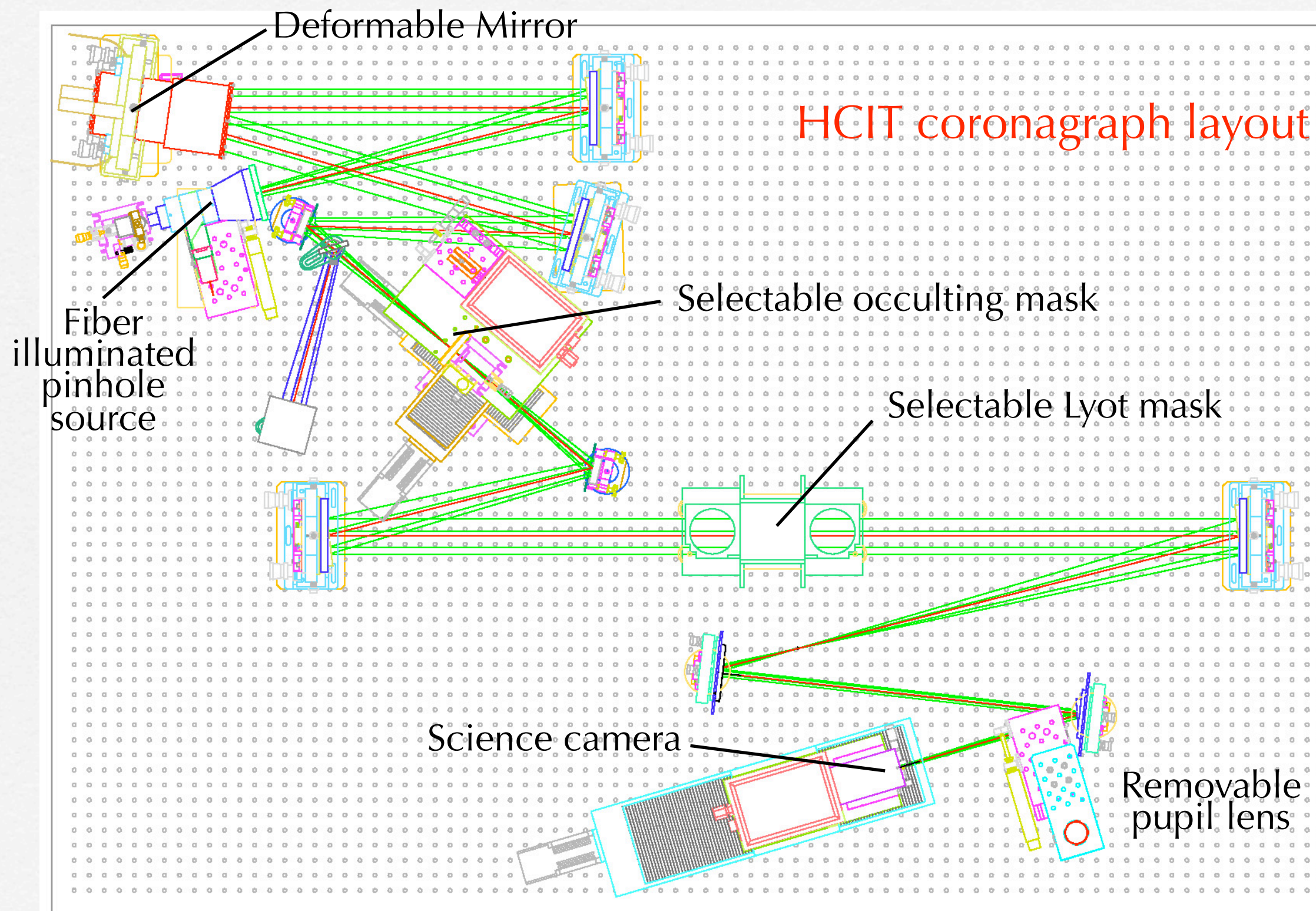
Lyot mask



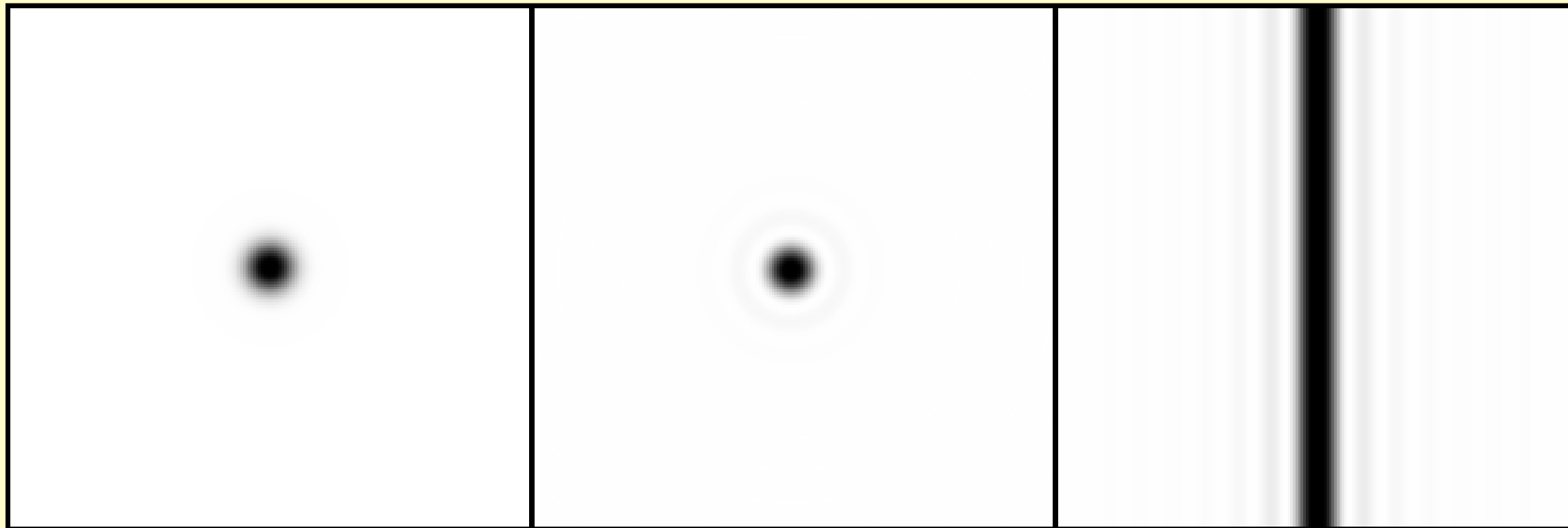
HCIT facility

HCIT coronagraph optical system resides in a vibration-isolated and temperature-stabilized vacuum facility in JPL's Optical Interferometry Development Laboratory.





Diverse coronagraph apodizations are available



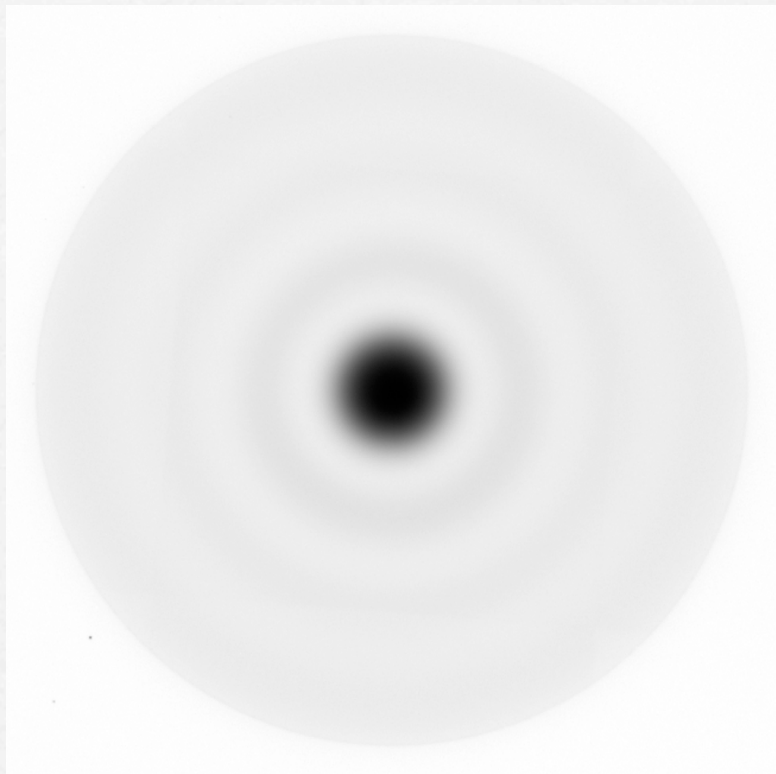
$$\left[1 - e^{-(r/\sigma)^2}\right]^2$$

$$\left[1 - \left[\frac{2J_1(\pi r/w)}{(\pi r/w)}\right]^2\right]^2$$

$$\left[1 - \left[\frac{\sin(\pi x/w)}{(\pi x/w)}\right]^2\right]^2$$

Transmittance profiles for three candidate occulting spot apodizations, all of which have been implemented in HEBS glass for the HCIT coronagraph. From left to right: a classical gaussian profile (Ftaclas 1990), a band-limited Bessel profile, and a linear sinc² profile (Traub and Kuchner 2001).

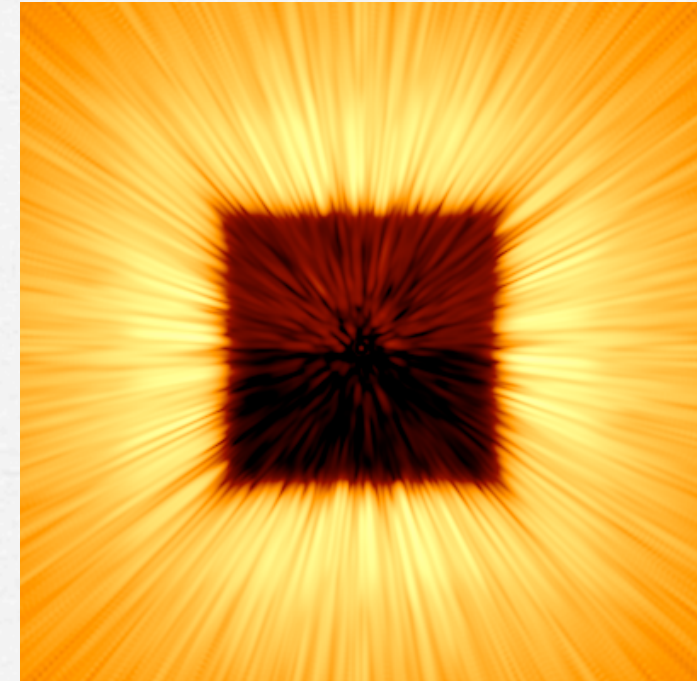
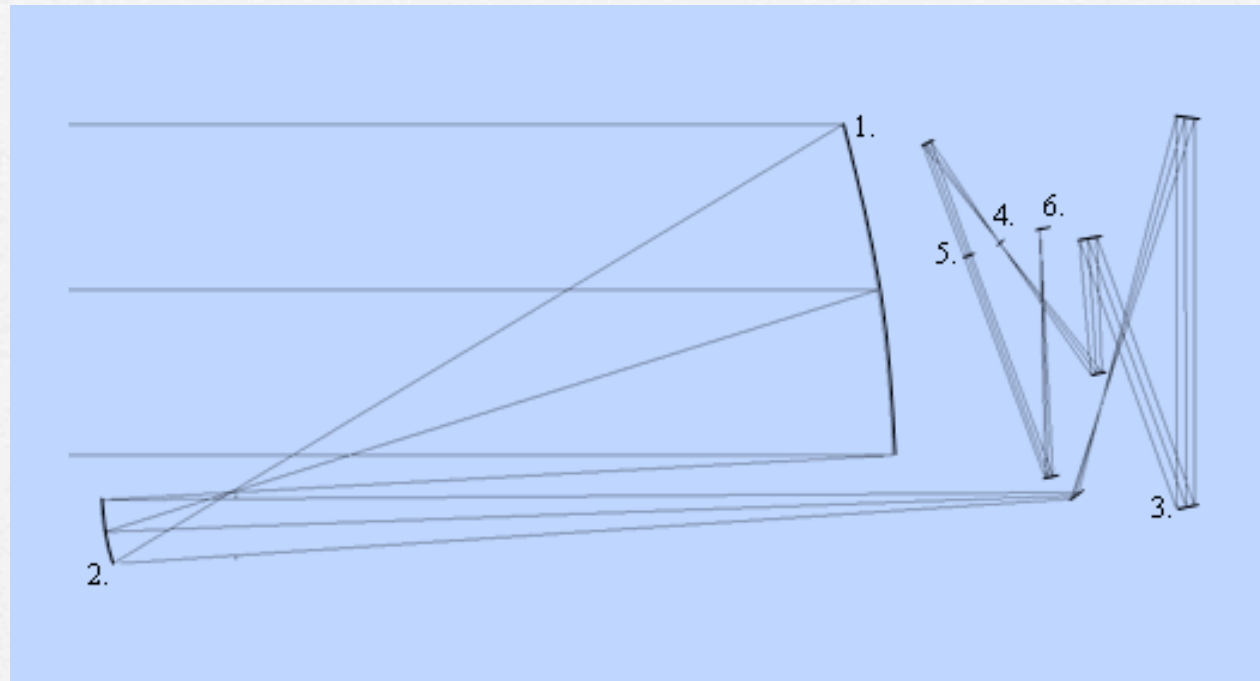
Apodized occulting masks are written at JPL's MDL



Coronagraph occulting spots, such as the measured circular sinc² profile at left, are written in HEBS glass with the 100 keV electron beam lithography system at JPL's Microdevices Laboratory. Spot measures 0.12 mm at the half transmittance contour of the central occulting spot. Optical densities up to OD 10 have been demonstrated.

Measurement of high-contrast attenuation profiles and associated phase shift profiles provide feedback for the manufacturing process.

Our models are validated by experiment --
Experiments are guided by our models

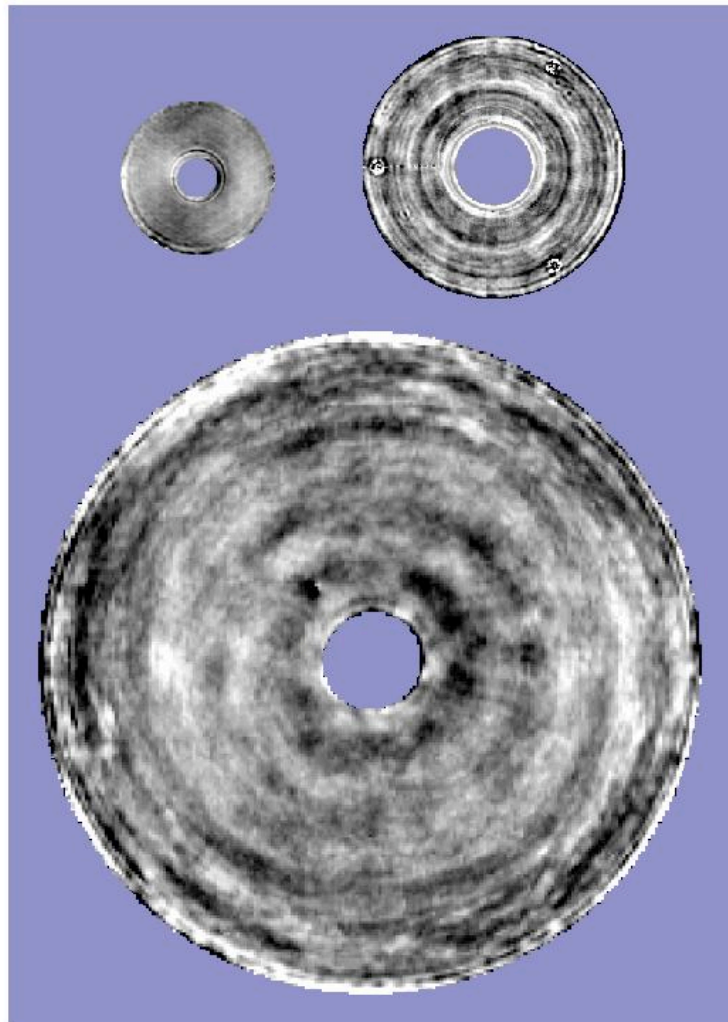


At left: The elements of representative telescopes and cameras have been implemented in a predictive diffractive and ray-trace optical model that include spatial low and mid-frequency figure errors and polarization characteristics of the mirror coatings. DM has been adjusted to compensate for both phase errors and phase-induced amplitude errors in the wavefront, providing the deepest contrast in the lower half of the dark field.

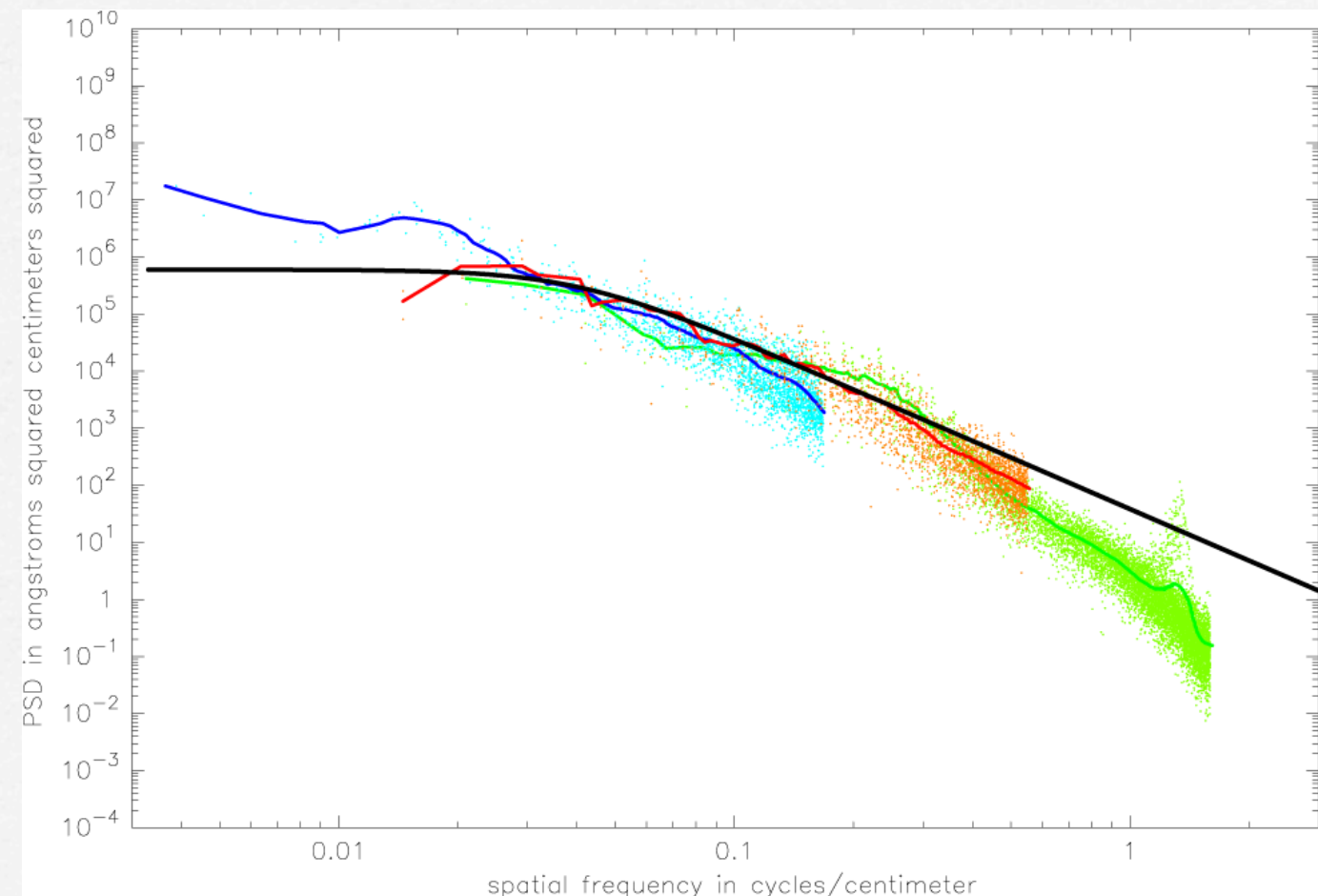
At right: Predicted star background (and high contrast dark field) at the focal plane of an actively corrected coronagraphic space telescope.

Wavefront correction is required

- ❑ State-of-the-art for large primary mirrors falls short of requirements for planet detection.
- ❑ This has been recognized since 1987:
 - ❑ The Circumstellar Imaging Telescope required optics smoother than HST by a factor of 15 or more to detect Jupiters at 10 pc (Terrile & Ftaclas 1987).
 - ❑ An improvement in HST PM surface figure by a factor of 200 between 0.06 and 6.0 μm was recommended to search for planets around 100s of nearby stars (Brown and Burrows 1987).
- ❑ Active optical correction can be carried out with a small deformable mirror within the science instrument.

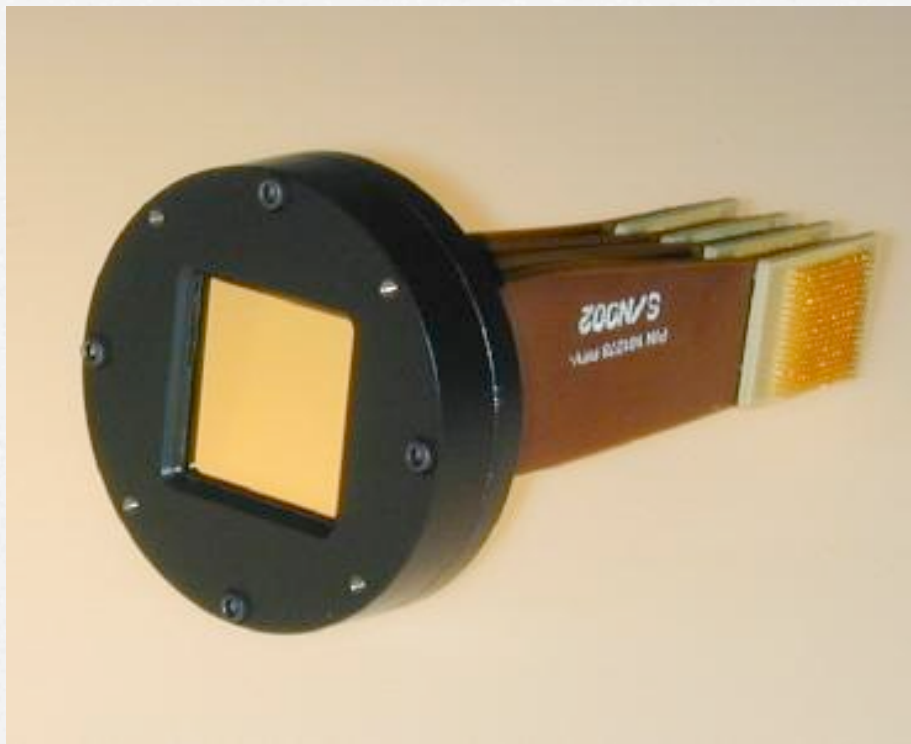


State of the Art for Large Optics



- ❑ These representative mirrors are HST (red curve), 6.5 m Magellan (blue) and a 1.5 m Kodak developmental lightweight mirror (green).
- ❑ State of the art for large mirror surface figure currently requires active correction to meet coronagraph wavefront requirements.

Progress with DM technology

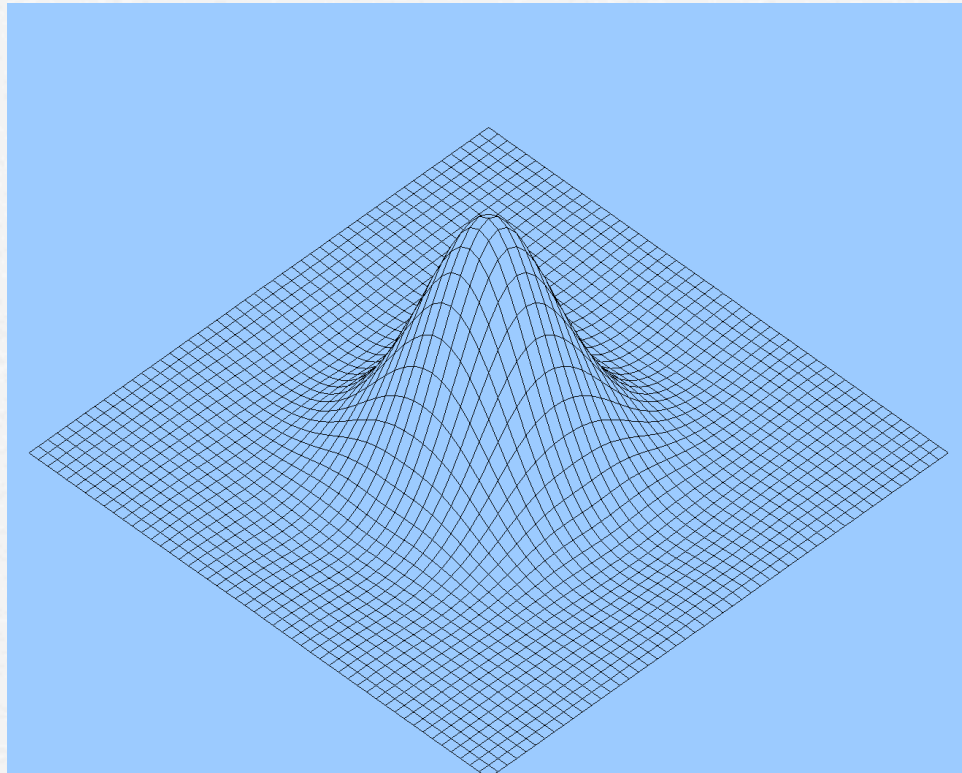


This is the fifth in a series of Gen2 32x32 mm DMs delivered to JPL by Xinetics. DM surface is polished to $\lambda/100$. Active figure control is better than 0.03 nm.

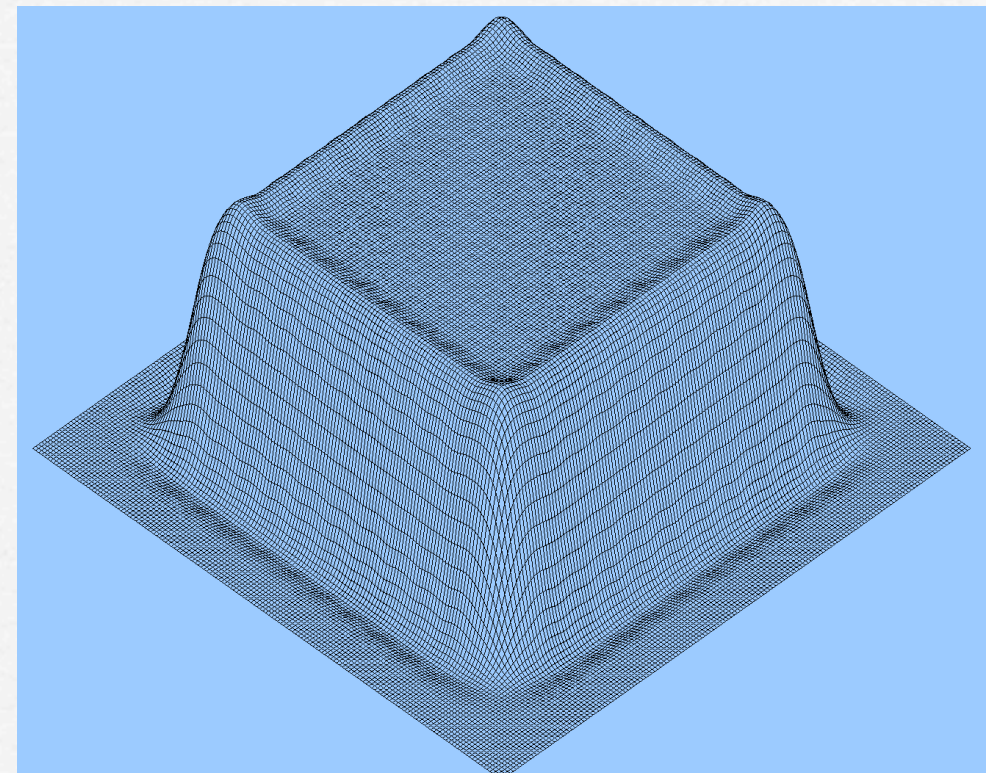


This is the first Gen2 64x64 mm DM delivered to JPL. Mirror and 4096 channel driver are ready for installation in the HCIT for calibration.

DM surface influence is well understood

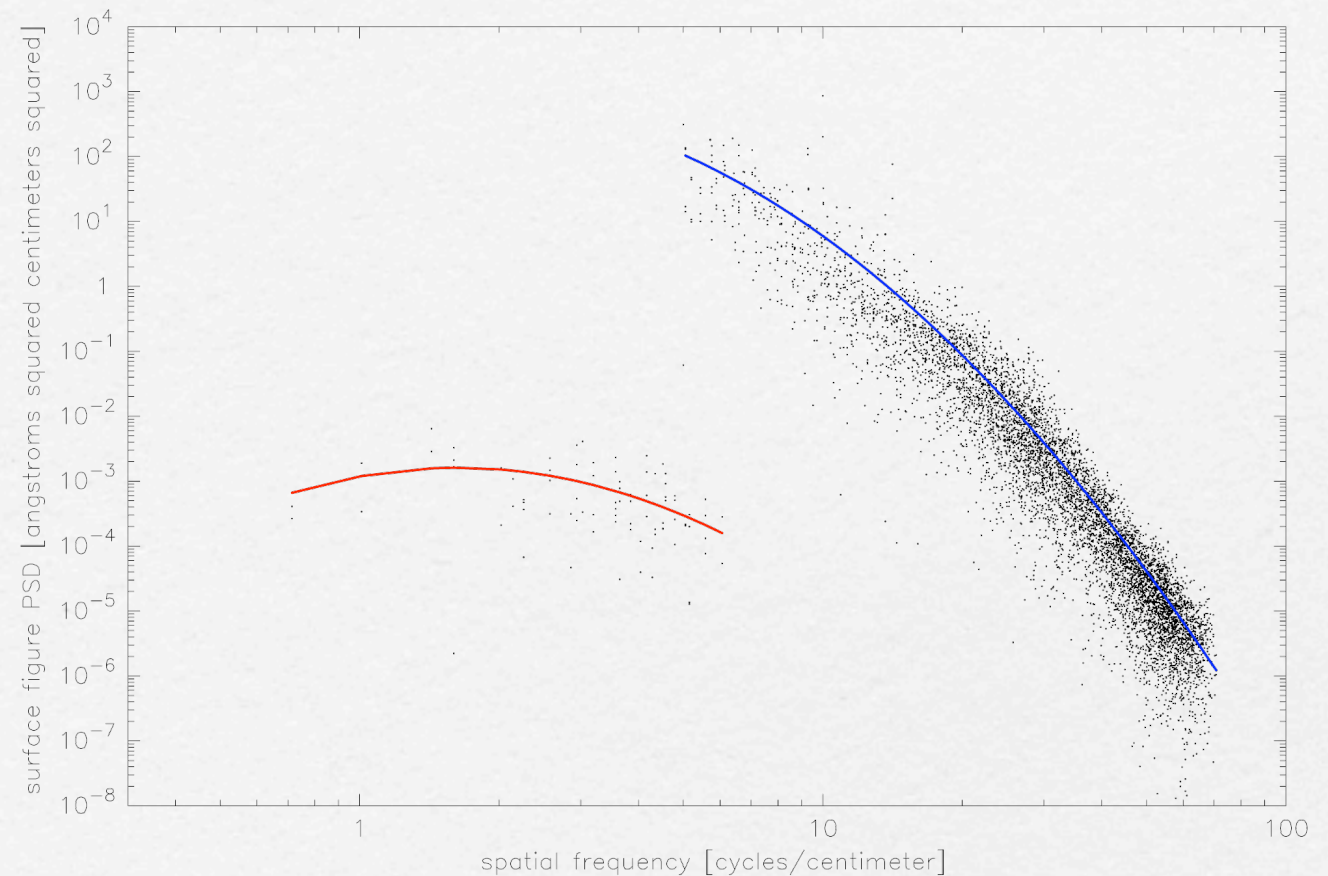
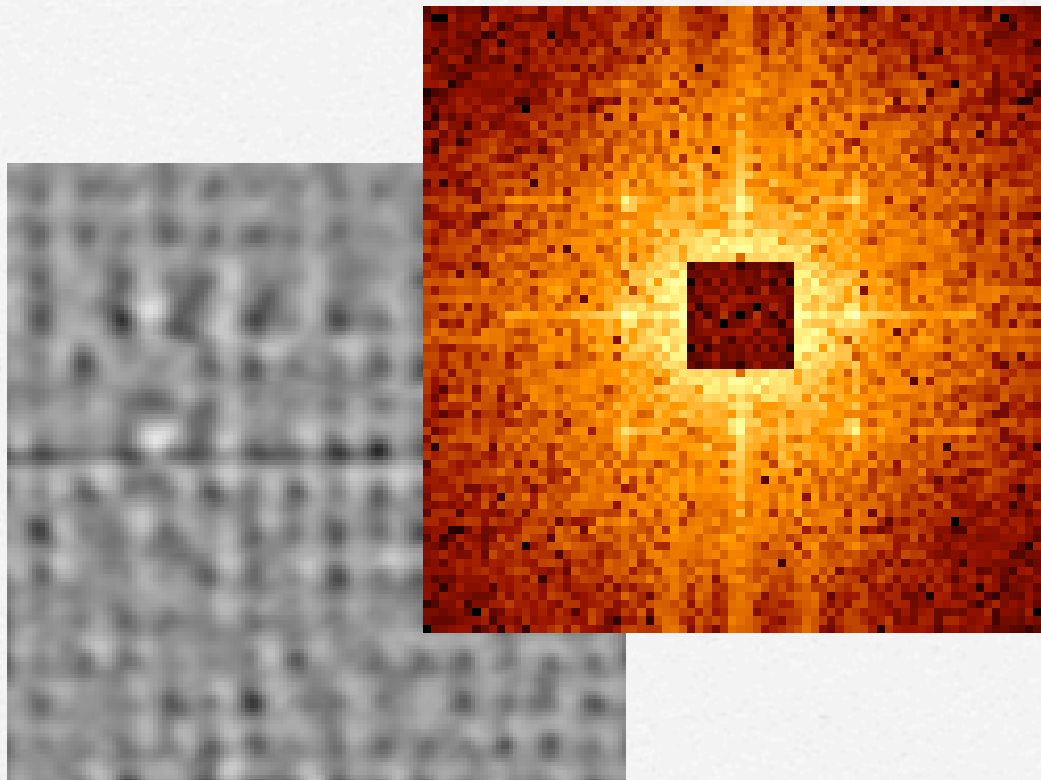


At left: The empirical surface deformation profile of a single actuator.
Grid spacing is 0.1 mm. Actuators are positioned in a square array with 1 mm pitch.



At right: Mirror surface predicted by linear superposition of actuator influence profiles
in an 11x11 actuator block pattern.

Mirror surface PSD meets coronagraph requirements



At left: Measured surface figure phase map quantifies the match of the deformable mirror to a target reference mirror surface. Quilting pattern corresponds to the 1mm pitch of the underlying actuators. In color: surface figure PSD displays “dark-field” control of the critical spatial frequencies.

At right: PSD analysis of the surface figure (PSD in $\text{\AA}^2 \text{cm}^2$ vs spatial frequency in cm^{-1}) illustrates control at spatial frequencies below Nyquist (red) and beyond Nyquist (blue), and the distinct region below Nyquist with 0.25 Angstrom rms surface figure control.

Wavefront sensing is simpler in space

- ❑ High contrast coronagraphy, working well enough to detect planets orbiting nearby stars, will require an exceptionally well corrected optical wavefront.
- ❑ A space telescope benefits magnificently in a space environment, hence our motivation.
- ❑ No atmosphere to produce kHz seeing, wind deflections, temperature fluctuations
- ❑ Stability time scales are determined mainly by the response of telescope optics to externally imposed thermal gradients.
- ❑ Thermal characteristics are subject to design and validation by test prior to launch.

New WFS methods are available to a coronagraph

- ❑ Active coronagraph adds two important items to the WFS&C toolbox:
 - ❑ DM provides deterministic wavefront phase diversity.
 - ❑ Occulter removes core of the image, providing higher S/N view of surrounding field of speckles associated with higher-order wavefront errors.
- ❑ HCIT demonstrates these techniques to the required precision for the first time.

Wavefront sensing is held to a high standard in space

- ❑ Surface figure can be measured to 0.0001 waves or better in a laboratory michelson interferometer (Gursel et al. 2003))
- ❑ Gerschberg-Saxton wavefront retrieval in the HCIT is repeatable to 0.0001 waves (Green et al. 2003))
- ❑ Lyot-plane wavefront sensing in the HCIT coronagraph is repeatable to 0.0001 waves (Moody et al. 2003)
- ❑ Speckle nulling at the HCIT coronagraph focal plane provides wavefront information accurate to 0.0001 waves (Burrows et al 2004).
- ❑ These techniques are compatible with space observatory operations, leading to mission designs that exploit the opportunity for high acuity and high contrast imaging.

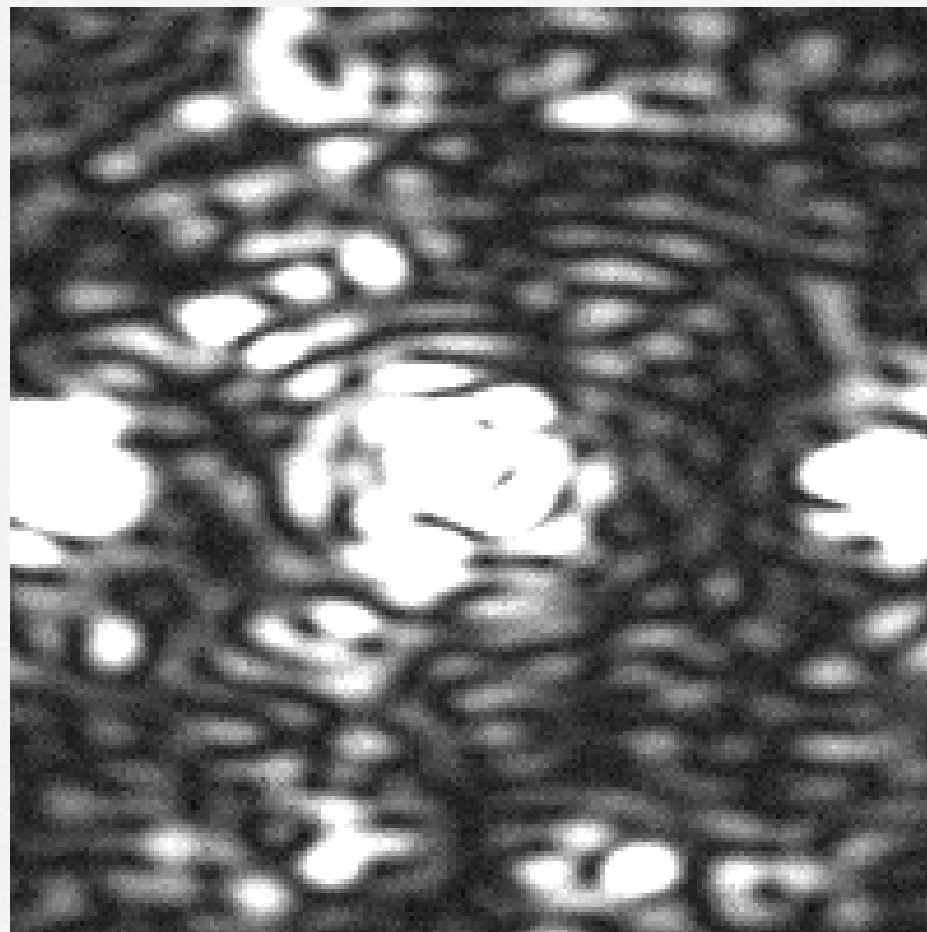
WFS&C with Speckle Nulling

- ❑ Algorithm works directly on the field of residual speckles in the dark field surrounding the star (Burrows et al. 2004).
- ❑ Converges on the best amplitude/phase solution for the dark field.
- ❑ Avoids non-common-path errors, since the science focal plane is also the WF sensor.
- ❑ Bypasses direct wavefront analysis, wavefront phase and amplitude errors can be recovered with analysis.
- ❑ Method is compatible with simultaneous observatory operations.

HCIT coronagraph contrast with a 32x32.3 DM

Speckle Nulling Demonstration

Central feature is residual 'starlight' at the center of the occulting mask. Target dark field is between the 4th and 10 Airy radii to the right of center. In the following movie sequence, a dozen speckles are targeted at each iteration, each speckle is probed with with six phase offset, then the optimal is selected.

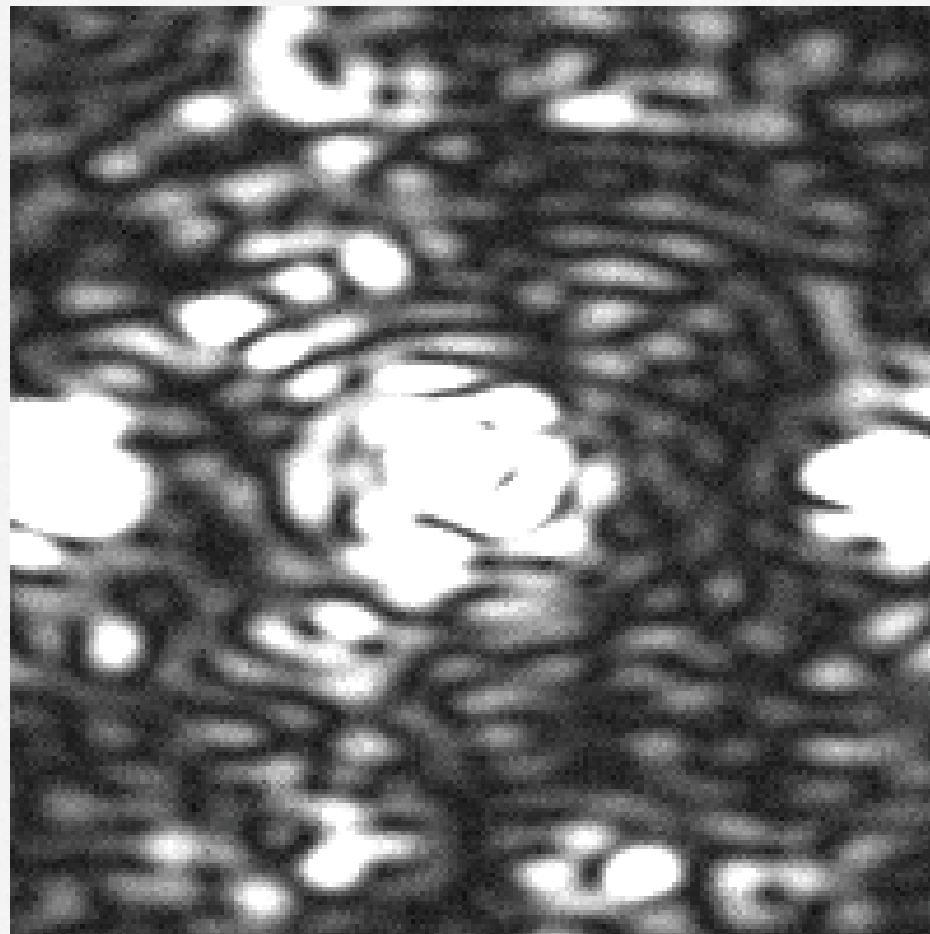


HCIT coronagraph image was obtained with a linear occulting mask in December 2003. Wavefront is corrected using speckle nulling entirely at the science focal plane (Burrows algorithm). Measurement is in narrowband light at 785nm wavelength.

HCIT coronagraph contrast with a 32x32.3 DM

Speckle Nulling Movie

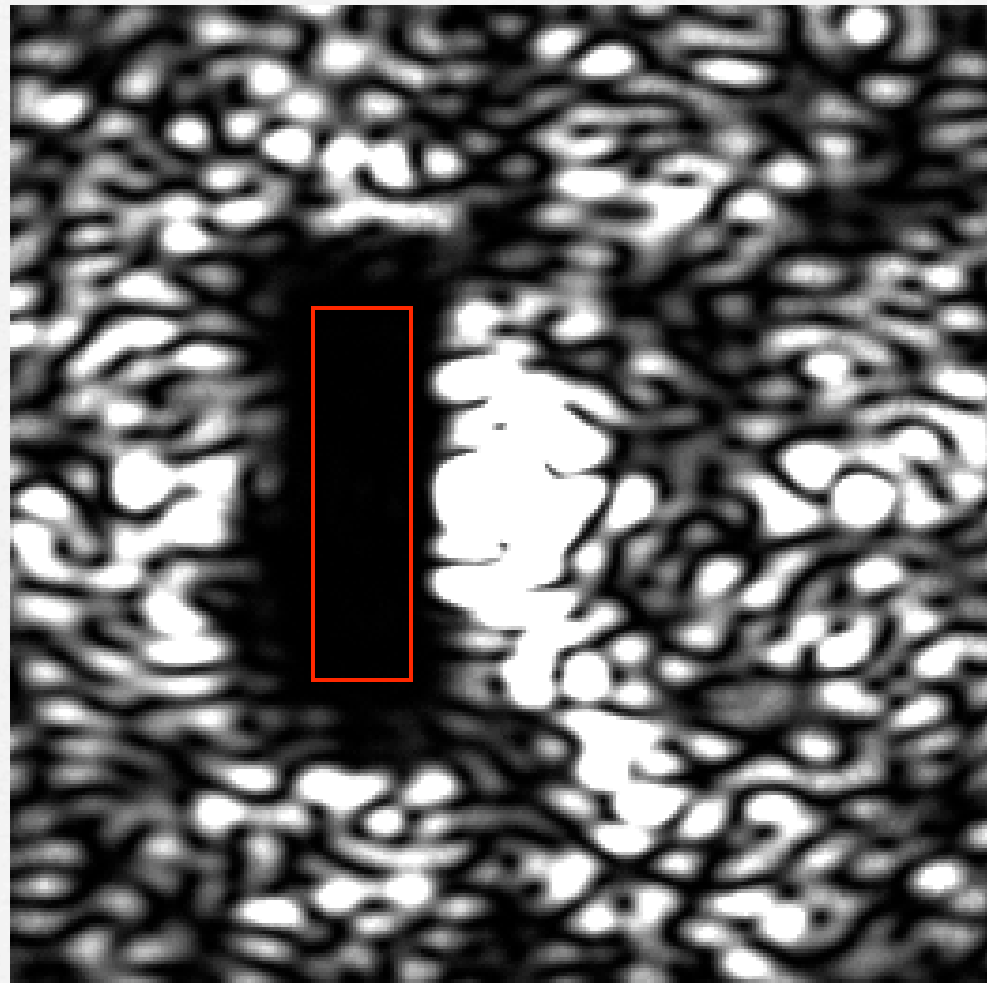
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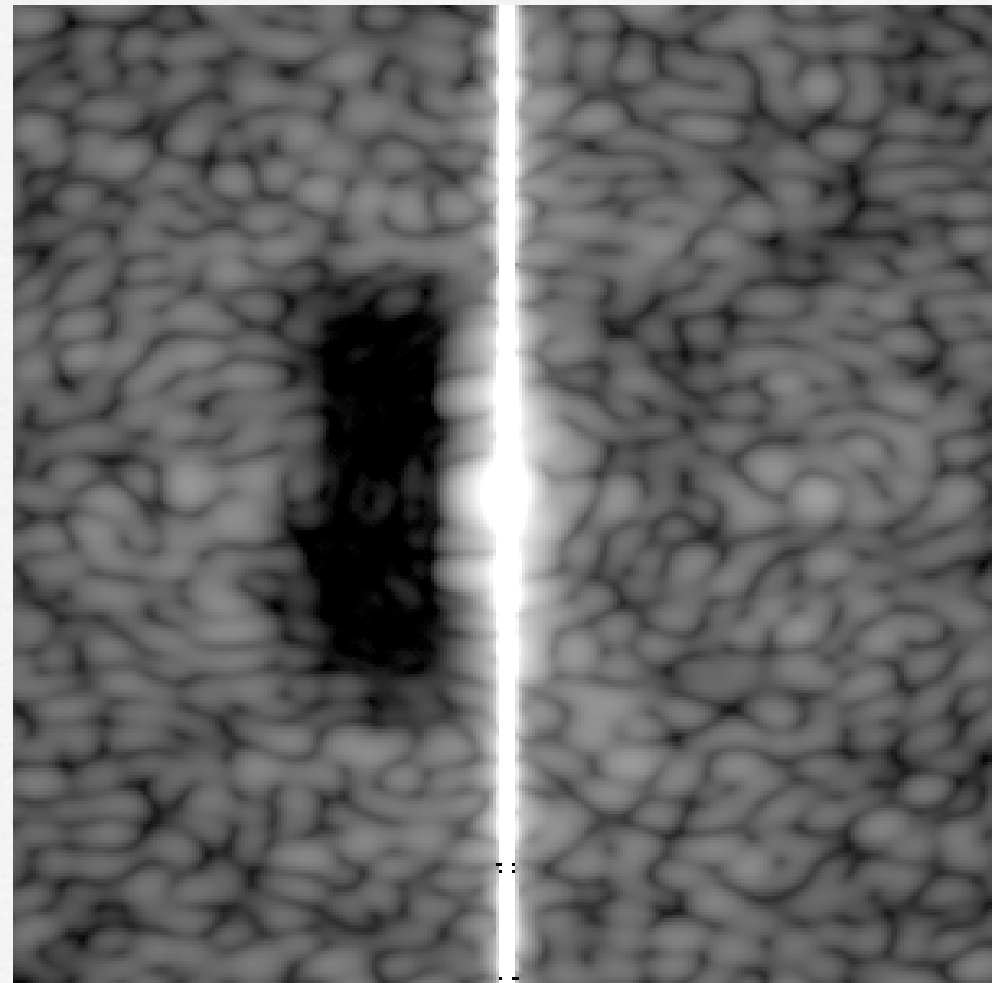
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HCIT coronagraph contrast with a 32x32.3 DM

HCIT image and target box



HCIT Contrast



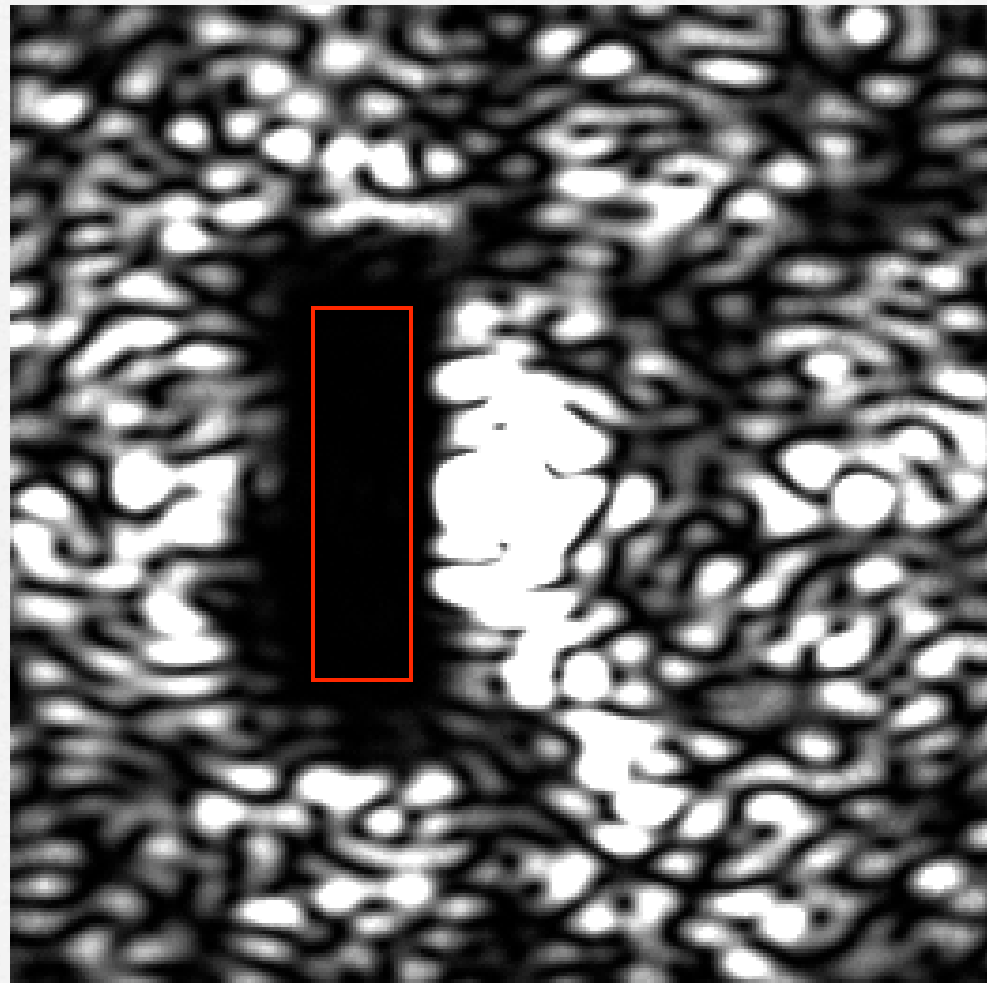
HCIT coronagraph image was obtained with a linear occulting mask in June 2004.
Inner boundary of the target box is 4 Airy radii to the left of the suppressed 'star' image.
Average contrast in the target box is 1.5×10^{-9} in 785 nm narrowband (laser) light.

Open-loop contrast is stable to 1×10^{-10} / hour.

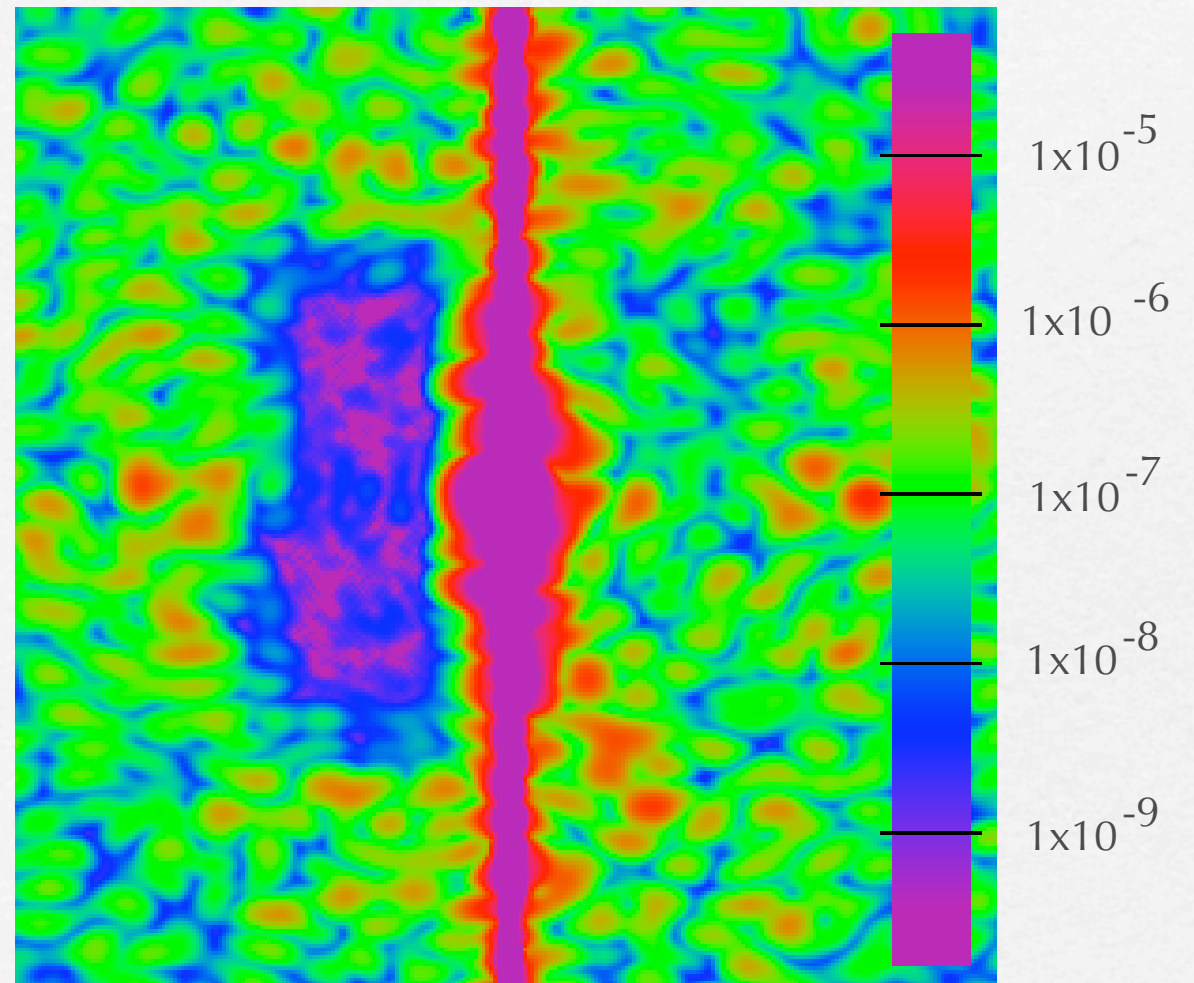
Same contrast levels are measured for 800 x 10 nm FWHM white light.

HCIT coronagraph contrast with a 32x32.3 DM

HCIT image and target box



HCIT Contrast



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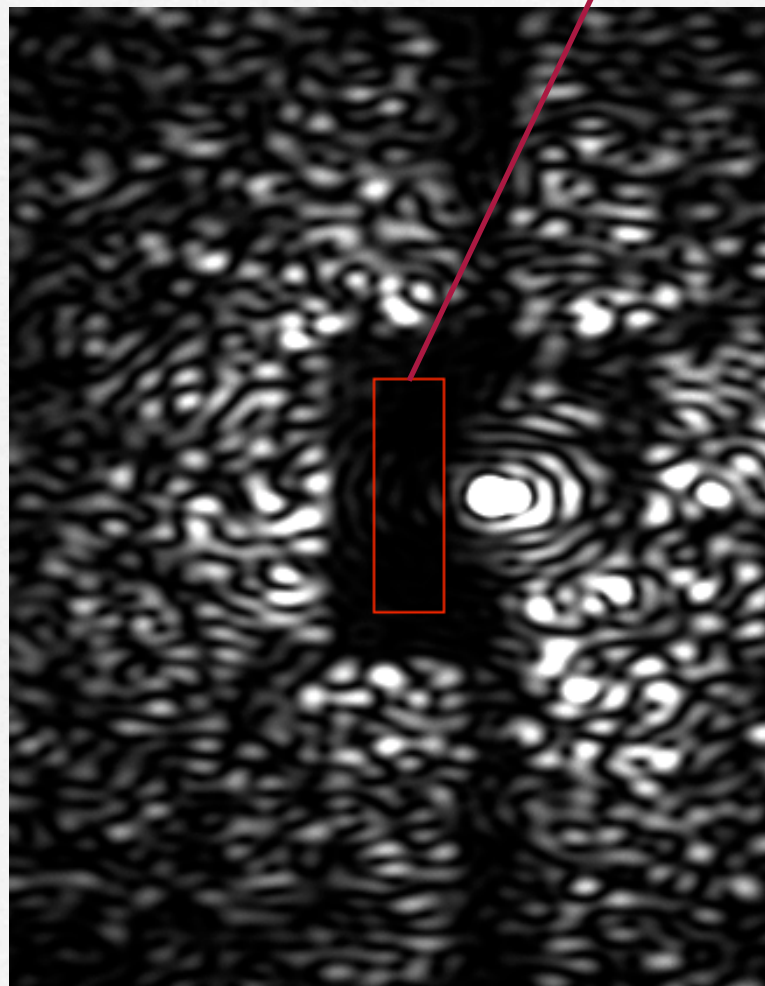
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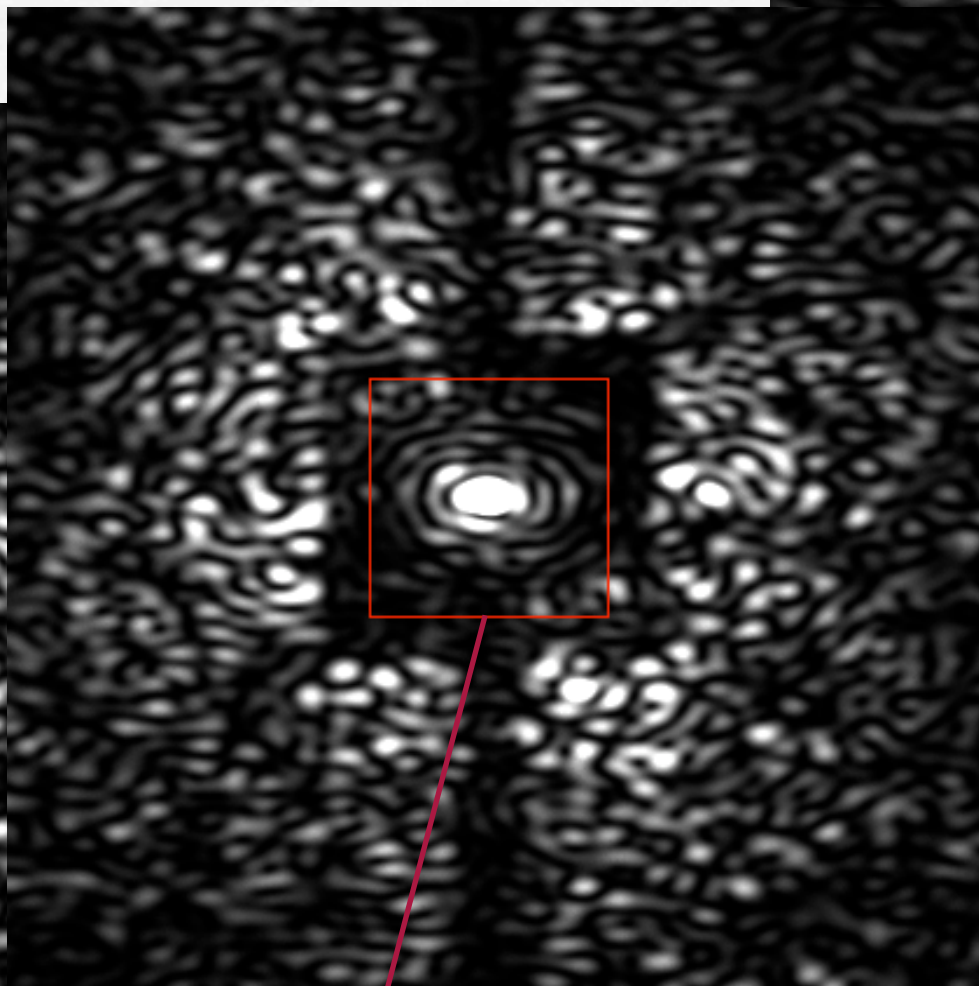
HCIT coronagraph results with the 32x32 DM

Various dark field solutions

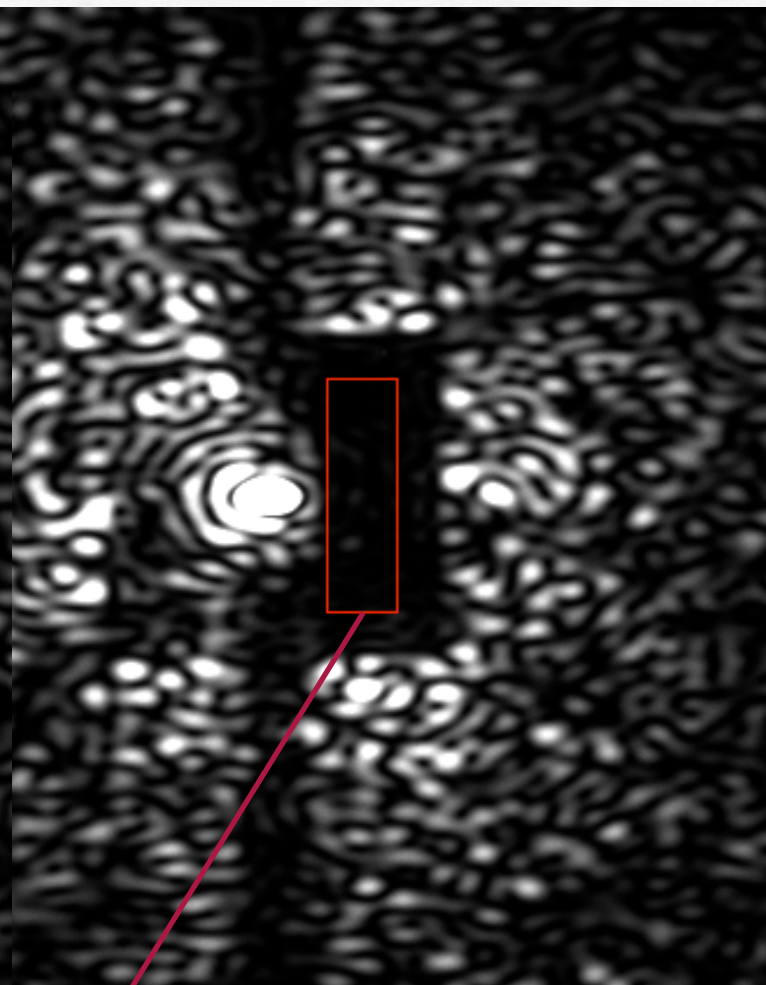
Amplitude and phase
solution on the left side



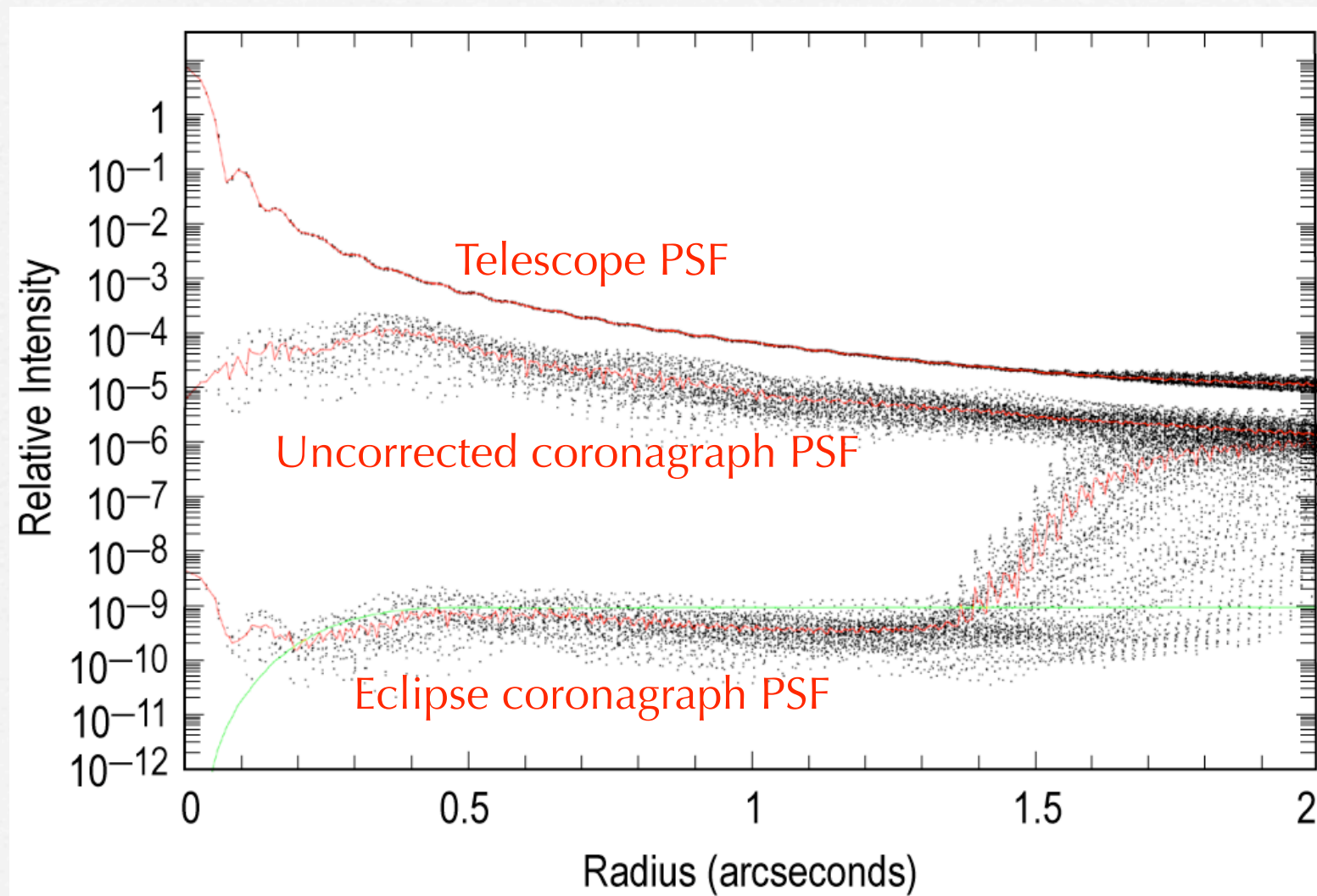
Wavefront phase
solution on both sides



Amplitude and phase
solution on the right side



These experiments validate predictive models



V-band point spread functions (PSFs) for (top) a 1.8 meter unobscured telescope with surface figure similar to HST; (middle) with the addition of a coronagraph similar to HCIT, but without DM wavefront corrections; and (bottom) an actively-corrected coronagraph similar to HCIT. This is the Eclipse concept. The green curve traces the peak brightness of a planet companion fainter than the star by a factor of 10^{-9} .

HCIT experiments guide hardware development, validate predictive models, evolve the control algorithms, and help forecast space coronagraph performance.

HCIT advances space coronagraph technology

- ❑ Verification and refinement of predictive optical models
- ❑ Development of hardware technologies to TRL 5/6
- ❑ Development of wavefront sensing and control algorithms viable for flight operations
- ❑ Identifies fundamental physical limitations that require to alternative approaches
- ❑ Prioritization of technical challenges guides the sequence of coming experiments
 - ❑ Predictive optical models provide the roadmap
 - ❑ Candidate coronagraph apodizations are numerous and diverse
 - ❑ Demonstration of contrast in white light of various wavelengths and bandwidths
 - ❑ Investigation of open-loop stability of the DM settings
 - ❑ Mirror coatings and optical layout control polarization and cross-polarizations
- ❑ Practical laboratory experience provides insight and guidance for mission design, including requirements for alignment stability, S/N at the science focal plane, and overall complexity

Summary

- ❑ The HCIT demonstrates high-contrast imaging with active wavefront sensing and control
 - ❑ Coronagraph occulting mask has selectable forms.
 - ❑ “Star” is a pinhole illuminated with a 785nm laser diode or filtered white light.
 - ❑ Wavefront knowledge is derived entirely at the science focal plane.
 - ❑ Wavefront is corrected with a precision deformable mirror (DM) at the pupil.
- ❑ WFS&C speckle nulling algorithm clears a dark field to one side of the occulted star.
 - ❑ Algorithm manipulates background speckles in the science focal plane.
- ❑ Complements other WFS&C techniques.
 - ❑ Eliminates errors due to non-common paths to science focal plane and WF sensor.
 - ❑ Requires no mechanical motions (such as focus) in the telescope optics.
- ❑ Work is ongoing to refine the focal-plane speckle-nulling algorithm.
 - ❑ Clearly defined “half dark field” averages 1.5×10^{-9} contrast.
 - ❑ Contrast is 4×10^{-9} at 4 Airy radii from the star.
- ❑ Laboratory measurements provide validation of optical models.

End